AFRL-AFOSR-VA-TR-2017-0007

Volumetric Combustion Diagnostics

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01/03/2017
Final Report

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Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/RTA1

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
20-12-2016	Final report	30 Sept 2014 to 29 Sept 2016

4. TITLE AND SUBTITLE
Volumetric Combustion Diagnostics

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-14-1-0386

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Lin Ma

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Virginia Tech
Sponsored Programs 0170
BLACKSBURG, VA 24061-0001

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Office of Scientific Research
875 N. Randolph, Ste.325
Arlington Virginia, 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
AFOSR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution A - Approved for public release

13. SUPPLEMENTARY NOTES
None

14. ABSTRACT
This two-year project is aimed at establishing advanced diagnostics techniques for obtaining volumetric measurement of key combustion properties. The proposed techniques are designed to generate instantaneous volumetric (i.e., three-dimensional, 3D) data without scanning or raster, and thusly to enable measurement rate in the multi-kilohertz range, directly addressing a key experimental need identified in the BAA. Six specific topics have been investigated during this project: 1) the establishment of a unified framework for volumetric tomography, 2) the investigation and validation of Volumetric Chemiluminescence imaging (VCHEM), 3) the investigation and validation of Volumetric Laser Induced Fluorescence (VLIF), 4) the investigation and validation of Volumetric Particle Image Velocimetry (VPIV), 5) the use of fiber bundles in volumetric tomography, and 6) algorithms for data Analysis and post processing.

15. SUBJECT TERMS
3D combustion diagnostics, volumetric diagnostics, laser diagnostics, tomography, LIF

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
				16	Chiping Li
					19b. TELEPHONE NUMBER *(Include area code)* 703-481-6930

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Final Report

Volumetric Combustion Diagnostics

AFOSR Grant Number: FA9550-14-1-0386

Period of Research: 09/30/2014 to 09/29/2016

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Dec 20, 2016

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Abstract

This two-year project is aimed at establishing advanced diagnostics techniques for obtaining volumetric measurement of key combustion properties. The proposed techniques are designed to generate instantaneous volumetric (i.e., three-dimensional, 3D) data without scanning or raster, and thusly to enable measurement rate in the multi-kilohertz range, directly addressing a key experimental need identified in the BAA. The following is a list of the specific objectives proposed and the accomplishments that we have achieved during the first year of the project under each objective.

1. A Unified Framework for Volumetric Tomography

This objective was successfully completed. A unified mathematical framework for obtaining 3D information from multiple projection measurements has been established, and the corresponding tomographic algorithm developed. The framework is applicable to all the subsequent research topics listed below.

2. Volumetric Chemiluminescence Imaging (VCHEM)

This objective was successfully completed. A VCHEM technique was developed and demonstrated in highly turbulent flames to combine chemiluminescence (or emission spectroscopy in general) and tomographic imaging to enable volumetric measurement of several key properties, including flame topography, curvature, surface area, and volume.

3. Volumetric Laser Induced Fluorescence (VLIF)

This objective was partially completed, and will continue into the second year. We have developed and demonstrated a VLIF technique that can extend the well-established PLIF (planar LIF) to volumetric measurement of species concentration. The VLIF technique used a thick laser sheet (or beam) to excite CH radicals in a volume. Measurements have been conducted in various flames, ranging from laminar to highly turbulent flames. Further data processing is underway.

4. Volumetric Particle Image Velocimetry (VPIV)

This objective was partially completed and will continue into the second year. We have performed experiments to reconstruct the seeder distribution in 3D, and we are developing the correlation algorithms to calculate velocity.

5. Use of Fiber Bundles in Volumetric Tomography

This objective was successfully completed. We have developed customized fiber endoscopes and demonstrate them in a variety of 3D measurement campaigns, ranging from laboratory flames to a Mach combustor.

6. Data Analysis and Post Processing

This objective was partially completed and will continue into the second year. We have developed algorithms to extract key physics from the 4D datasets (three spatial dimensions and time) enabled by the volumetric diagnostics listed above. These algorithms included algorithms to extract flame topography, surface area, 3D curvature, and multi-dimensional POD (proper orthogonal decomposition). We will keep developing new algorithms as our experimental work progresses.

2. Research Efforts

2.1. A Unified Framework for Volumetric Tomography

This objective has been successfully completed. Our work under this objective has been detailed in [1] and [2].

A brief summary is provided here with the aid of Figure 1. Figure 1 shows the mathematical formation of the problem. We assume the measurement volume is cubical with a dimension of L that encompasses the region of interests in the flame. The measurement volume is discretized into n voxels in each direction with $n = L/\tau$, resulting in a total of n^3 voxels. Chemiluminescence photons emitted from each voxel will transmit through the imaging system and then reach the camera chip, forming an image (called a *projection*, P) as shown.

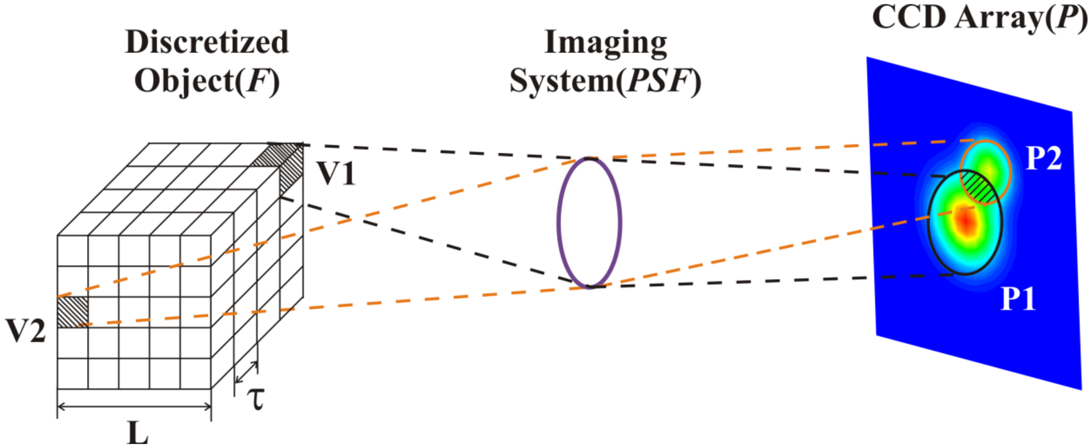


Figure 1. Mathematical formulation of volumetric diagnostic.

The projection of F on the camera chip is related to F itself via the point spread function as shown below:

$$P(x_P, y_P) = \sum_{x_F=1}^{n} \sum_{y_F=1}^{n} \sum_{z_F=1}^{n} F(x_F, y_F, z_F) \cdot PSF(x_F, y_F, z_F; x_P, y_P) \tag{1}$$

$P(x_P, y_P)$ represent the value of projection at a pixel located (x_P, y_P) on the camera chip; x_F, y_F, and z_F the indices of the voxels in the x, y, and z directions, respectively; n the total number of voxels in each direction as introduced above; *PSF* the point spread function defined as the projection formed at (x_P, y_P) by a point source located at (x_F, y_F, z_F) with unity intensity. Note that the *PSF* does not depend on F, but it depends on the lens used in the imaging system and the location and orientation of the imaging system. Physically, Eq. (1) states that the projection of F on pixel (x_P, y_P) is a weighted summation of signals contributed from all voxels' on this pixel, and the weighting factor is the point spread function (*PSF*). A hybrid algorithm that combined the ART (algebraic reconstruction algorithm) and TISA (tomographic inversion by simulated annealing) was developed to solve this problem.

2.2. Volumetric Chemiluminescence Imaging (VCHEM)

This objective has been successfully completed. Our work under this objective has been detailed in [2-4].

A VCHEM technique was developed and demonstrated in a range of flames, including laminar flame for validation purposes [2], highly turbulent flames [5], and supersonic flames [3, 4]. Based on the volumetric measurement, several key properties, including flame topography, curvature, surface area, and volume were extracted.

Here we use an example measurement in a Mach 2 combustor to illustrate the VCHEM diagnostics. This example involved a measurement campaign in collaboration with researchers at the Air Force Research Laboratory (Drs. Timothy Ombrello and Campbell Carter). The campaign combined endoscopic imaging and tomography, to enable 3D flame measurements in a Mach 2 combustor at a temporal rate of 20 kHz (i.e., 50 μs). Customized fiber endoscopes were applied to image the target flame from 8 different view angles simultaneously at 20 kHz. The images captured were then fed into a tomography inversion algorithm, frame-by-frame, to obtain 4D flame properties, including topography, surface area, volume, and curvature. These results are used to study both the ignition and stable operation of the combustor. Figure 2 below shows a photo of the experimental set up and an example of the 3D flame topography obtained during the ignition and stable operation stage.

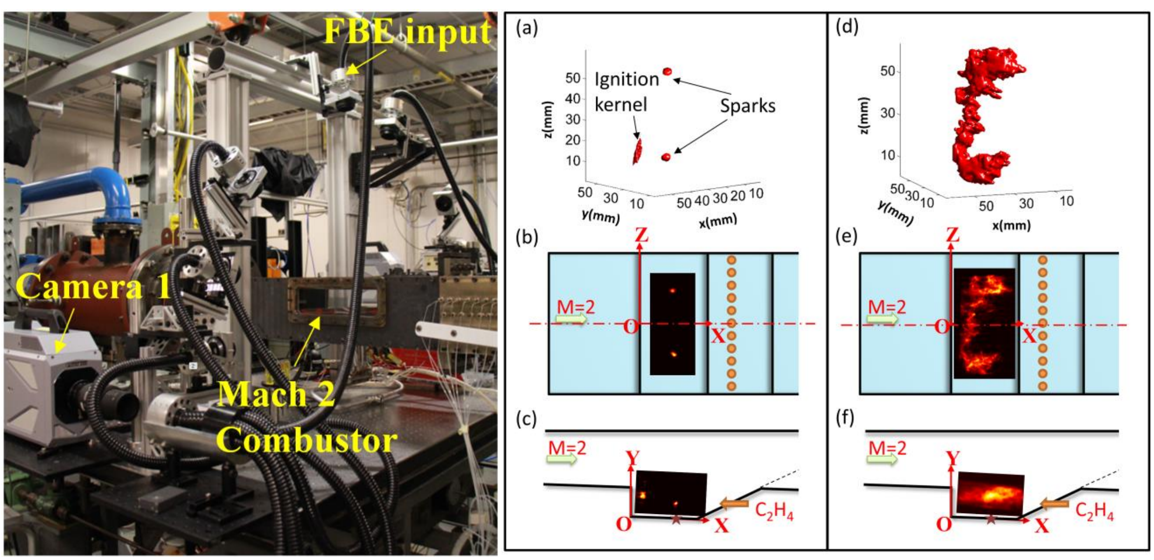


Figure 2. Application of the VCHEM diagnostic in a Mach 2 combustor and a set of example 3D reconstruction and images captured by the fiber endoscope from the top and side view for both the ignition (panels a, b, and c) and the stable operation stage (panels d, e, and f).

Such volumetric measurement capability enabled 3D information and provided valuable data to study the combustion processes. As an example, Figure 3 shows the volume the flame calculated from the 3D reconstructions for a fuel lean case (panel a) and a fuel rich case (panel b),

respectively. Results obtained on others cases were similar, and led to the same observations and conclusions discussed here. In these results, the contribution from sparks were separated out and excluded in these result. Both the fuel lean and rich results show two distinct stages: 1) the ignition stage during which the volume of the flame grew rapidly, and 2) the stable combustion stage during which the volume remained relatively stable. To quantify the transition time from the ignition stage to the stable combustion stage, here we defined time t_2 as the time that the flame volume reached the averaged of the stable stage. For instance, for the results shown in Figure 3a (fuel lean case), the average volume (during t=5 ms to 10 ms) was calculated first as shown, and the time when the flame volume first reached this value was then defined as t_2 (which was determined to be 3.5 ms in this case). For the results shown in Figure 3b for the first fuel rich case, t_2 was determined to be 5.6 ms in this case. The transition times for other cases were also determined from these 3D measurements, and these results show that the ignition kernel initiated earlier and transitioned into stable flames earlier than under fuel lean conditions than under fuel rich conditions. These observations are in agreement with past observations [6].

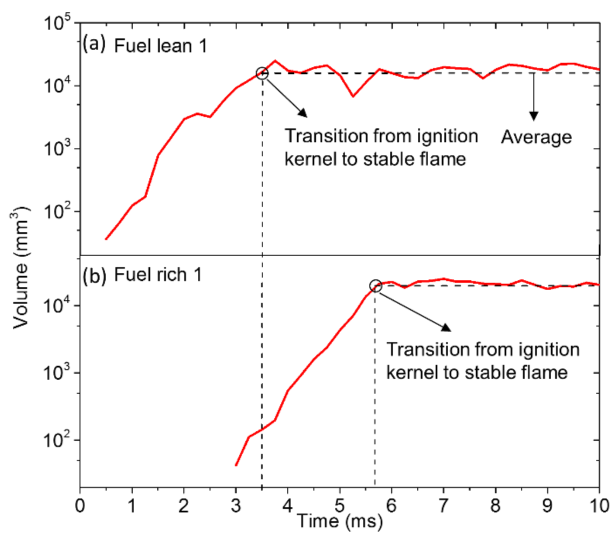


Figure 3. Measured 3D volume for fuel lean case 1 (panel a) and fuel rich case 1 (panel b).

2.3. Volumetric Laser Induced Fluorescence (VLIF)

This objective was completed and is summarized in [7-9] and [10].

We have developed and demonstrated a VLIF technique that can extend the well-established PLIF (planar LIF [11, 12]) to volumetric measurement of species concentration, and have demonstrated single-shot VLIF measurements in both passive [9] and reactive flows [8, 10]. Here we focus this report on the demonstration and validation of the VLIF technique in reactive flows based on CH radial. In these demonstrations and validations, the VLIF technique used a thick laser sheet (or beam) to excite CH radicals in a volume. Measurements have been conducted in various flames, ranging from laminar to highly turbulent flames. Figures 4 and 5

show an example set of VLIF measurements taken out of [7]. These measurements were obtained with a total of 5 intensified cameras based on CH radical in a highly turbulent jet flame (piloted). Figure 3 shows the measured projections at three different time instants, and Figure 5 shows the corresponding 3D VLIF reconstruction.

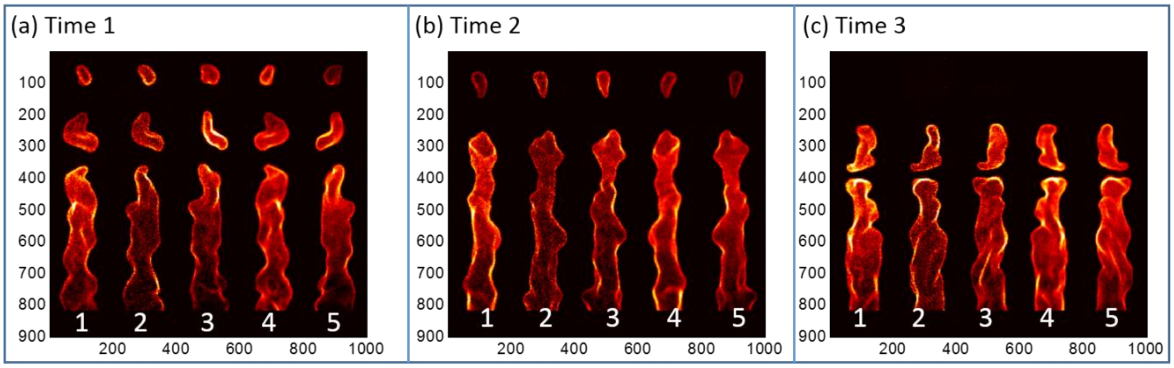


Figure 4. Example VLIF measurements based on CH radial of turbulent flames at three consequent time instants using a total of 5 cameras.

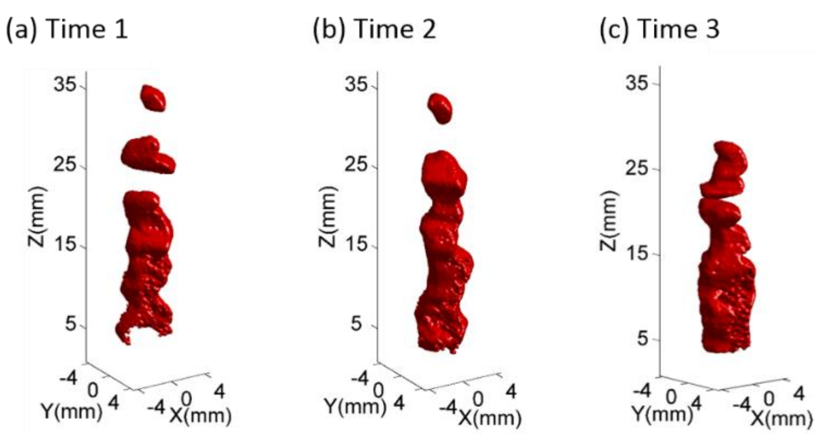


Figure 5. 3D VLIF reconstruction of instantaneous turbulent flame structures.

After the above demonstration measurements, a set of validation measurements were performed by a direct comparison between 2D (two-dimensional) and 3D VLIF in both laminar and highly turbulent flames. To accomplish such validation, planar LIF (PLIF) and VLIF measurements were simultaneously performed on both laminar and turbulent flames based on the CH radical. The PLIF measurements imaged a planar cross-section of the target flames across a 2D field-of-view (FOV) of 42×42 mm. The VLIF measurements imaged the same region in the target flame with a 3D FOV of 42×42×5 mm, with 5 mm being the thickness of the measurement volume. The VLIF signals generated in this volume were captured by five intensified cameras from different perspectives, based on which a 3D tomographic reconstruction was performed to obtain the 3D reconstruction of the CH radical (as a marker of the flame front). The PLIF measurements were then compared to a cross-section of the VLIF measurement to demonstrate

the feasibility and accuracy of instantaneous 3D imaging of flame topography and flame surface area in highly turbulent flames. Figure 6 shows a set of sample VLIF and PLIF projections to illustrate the nature of the experiments. The flame was generated with the HiPiolot burner operating on high flow rates, resulting in a highly turbulent flame with turbulent Reynolds number of 4,240 [13, 14]. Fig. 6a-e shows the measured VLIF projections by cameras 1-5 and Fig. ff shows the simultaneous PLIF measurements by camera 6. These images illustrate the volumetric nature of the VLIF signal, in contrast to the planar nature of the PLIF signal.

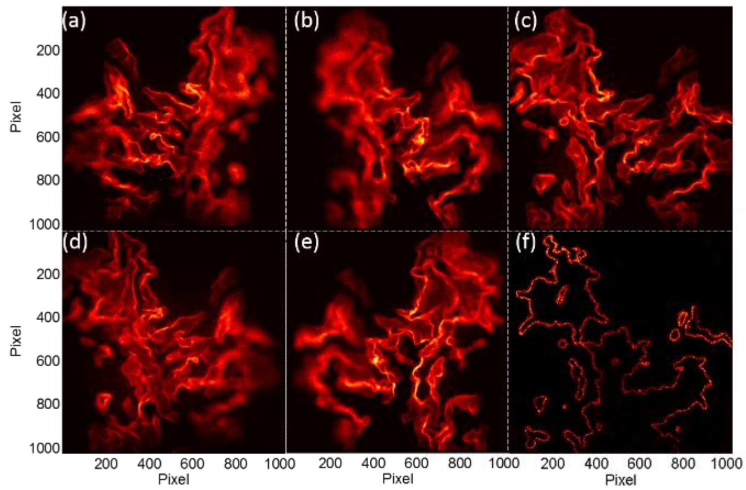


Figure 6. A set of example projections measured by camera 1 through 6. Panels (a) – (e): the VLIF projections captured by camera 1 through 5. Panel (f): the PLIF measurement captured by camera 6.

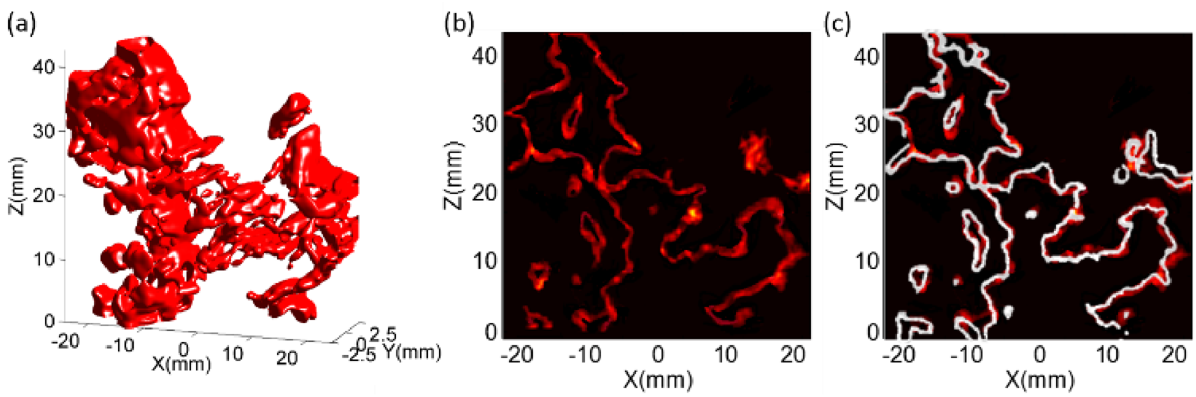


Figure 7. Panel (a): 3D VLIF measurement. Panels (b): the cross-section of the VLIF measurement at Y = 0 mm. Panel (c): comparison of VLIF and PLIF.

Based on the VLIF signal shown in Fig. 6a-e, the 3D distribution of CH was reconstructed using the tomographic algorithm detailed above. The reconstruction was performed on a measurement region of 45 × 45 × 5 mm, discretized into 256 × 256 × 28 voxels (resulting in a voxel size of 0.18 mm), as shown in Figure 7a. For direct comparison with the

PLIF measurements, the VLIF reconstruction at Y=0 mm (i.e., the central plane of the burner and the plane where the PLIF measurement was taken) was extracted and plotted in Fig. 7b. Fig. 7c directly compares this reconstruction against the PLIF measurement (shown in Fig. 6f) by overlaying the two measurements (with the PLIF measurement shown in white to aid the comparison). The good agreement observed in this comparison demonstrates the fidelity and accuracy of the VLIF technique to provide instantaneous 3D measurements of highly turbulent flames, resolving both the large-scale and small-scale structures of the turbulent flame. Note too that the results shown here are from the high-flow case, and the agreement is better for results processed from flames with lower turbulent intensity.

2.4. Volumetric Particle Image Velocimetry (VPIV)

This objective was completed and the results are summarized here. We have performed experiments to reconstruct the seeder distribution both in turbulent flows and static samples, and have developed and validated the correlation algorithms for calculating velocity. Figures 8 and 9 show a set of example results where we applied 5 cameras to turbulent jet flows seeded with water droplets and the 3D reconstruction of the distribution of the seeded water droplets. Based on such 3D reconstruction, a correlation algorithm was developed to obtain 3D3D (three dimensional and three component) velocity.

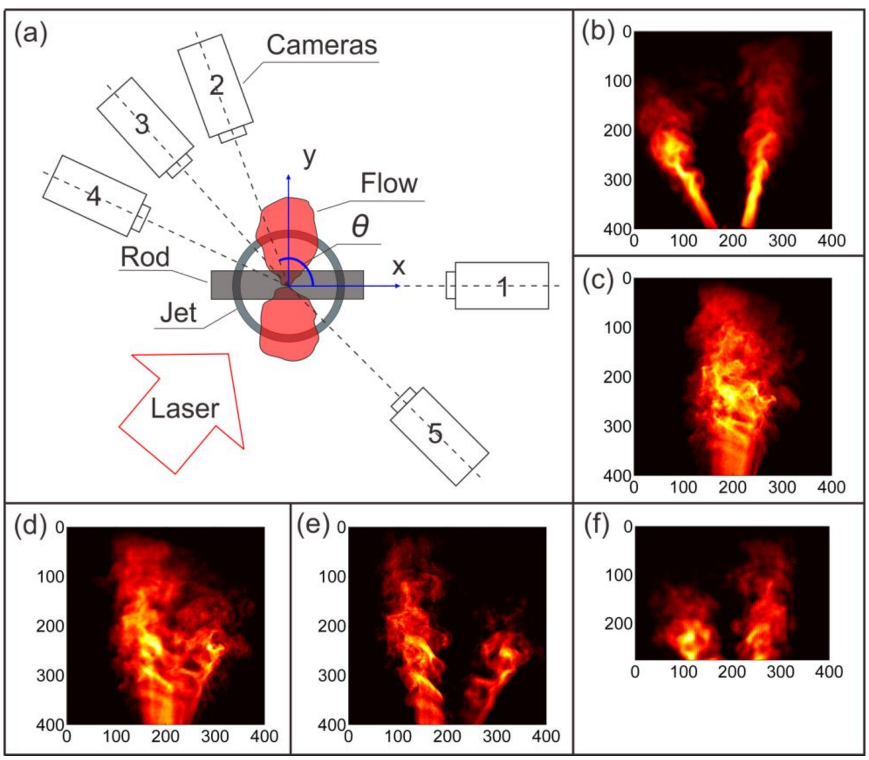


Figure 8. Experiments performed in a jet flow seeded with water droplets and a set of measured projections.

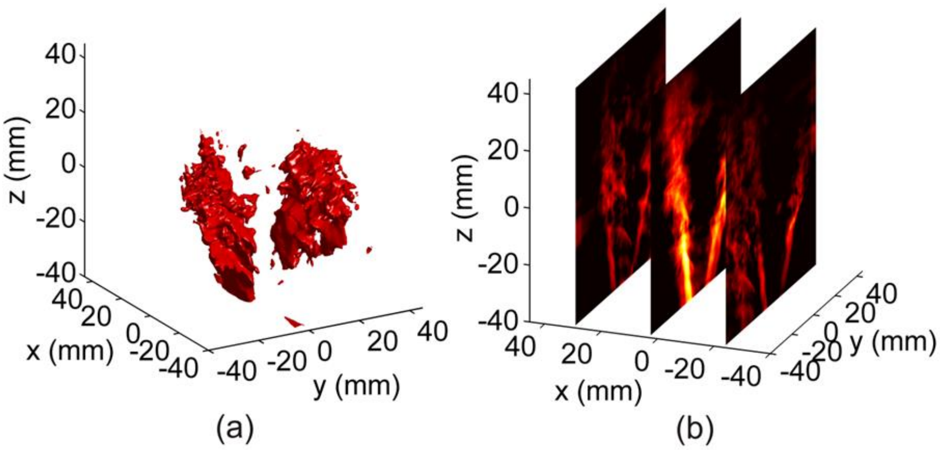


Figure 9. 3D reconstruction of the seeded water droplets. Panel (a): 3D rendering. Panel (b): cross-sectional view at three different locations.

To experimentally validate the above VPIV technique and the 3D correlation algorithm, a set of controlled measurements were designed and performed. The 3D measurements were performed based on the scattering light intensity of tracer particles seeded in a controlled cell. The particles were illuminated by a thick laser slab. The volumetric scattering signal was then simultaneously collected by a total of 6 cameras form 6 different orientations, based on which a 3D tomographic reconstruction was performed to obtain the 3D distribution of light intensity discretized into voxels. The reconstructed tomogram pair of the cell was then analyzed using a 3D cross-correlation program, resulting in the 3D3C velocity vector distribution over the domain of interest. The reconstructed velocity distribution was then compared to the ideal velocity distribution calculated from precisely controlled cell movement, both to provide a validation to tomo-PIV measurements and also to evaluate the accuracy of reconstructions. In each validation experiment, the location of the controlled cell was shifted by moving (or rotating) the cell to create a displacement for the seeded particles. Fig. 10 shows the vector distribution of the displacement field obtained using the tomographic and correlation algorithms. Fig. 10a shows the results when the controlled cell was moved translationally by 0.51 mm towards the positive x direction, and Fig. 10b shows the results when the controlled cell was rotated clock-wise (viewed from the top) by 2.5° around the center of the cell. The reconstruction and correlation was performed on a 30 × 30 × 30 voxels interrogation volumes at 75% overlap, resulting in a total of 117 × 117 × 37 displacement vectors (which is equivalent to velocity vectors). As seen from Fig. 10, the reconstructed displacement field agreed with the filed expected by moving and rotating the cell. The accuracy of the agreement is quantified in Fig. 11. Fig. 11(a) and 11(b) show the displacement error distribution corresponding to Fig. 10(a) and (b), respectively. Several observations can be made based on the results of Fig. 5. As seen, in both cases, the majority of the vectors were reconstructed accurately. More specifically, the error was within 3 pixels for more than 96% of the vectors in the translational case, and 85% in the rotational case.

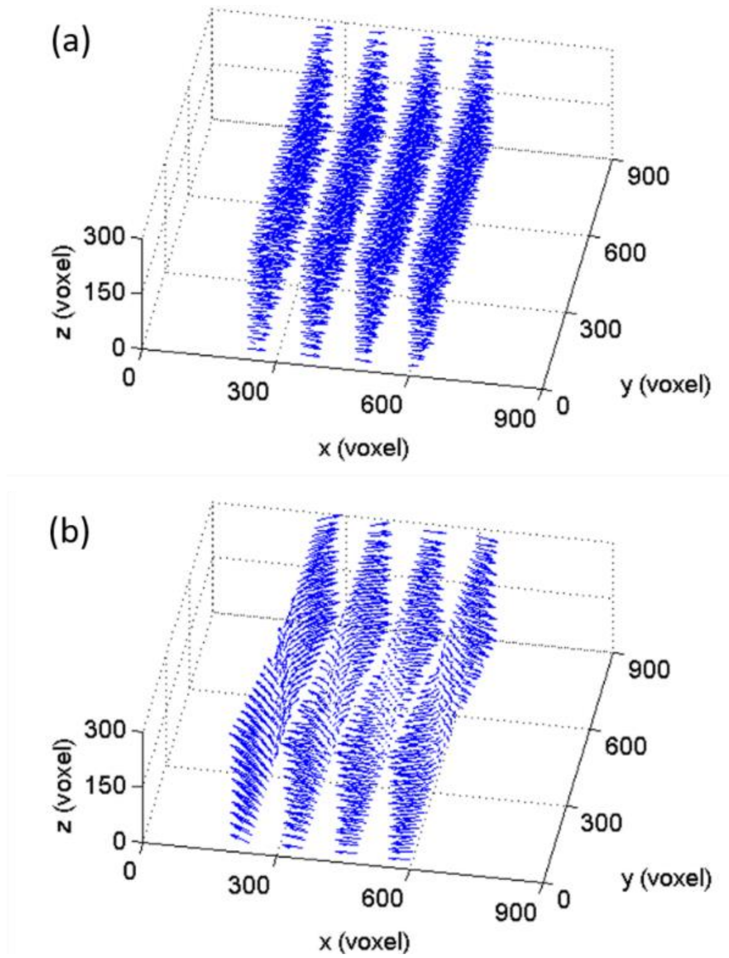


Figure 10. The vector distribution of the displacement field of translation (panel (a)) and rotation (panel (b)).

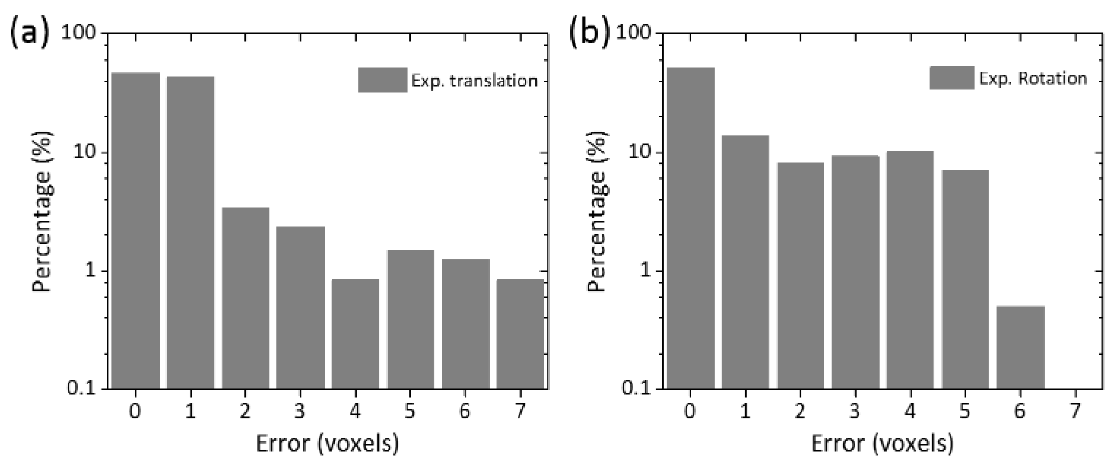
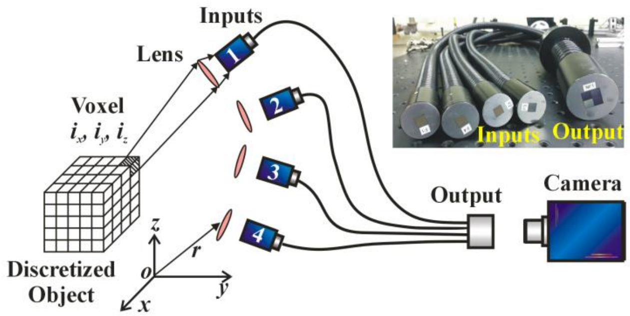


Figure 11. The displacement vector error distribution of the translation (panel (a)) and rotation (panel (b)) experiments.

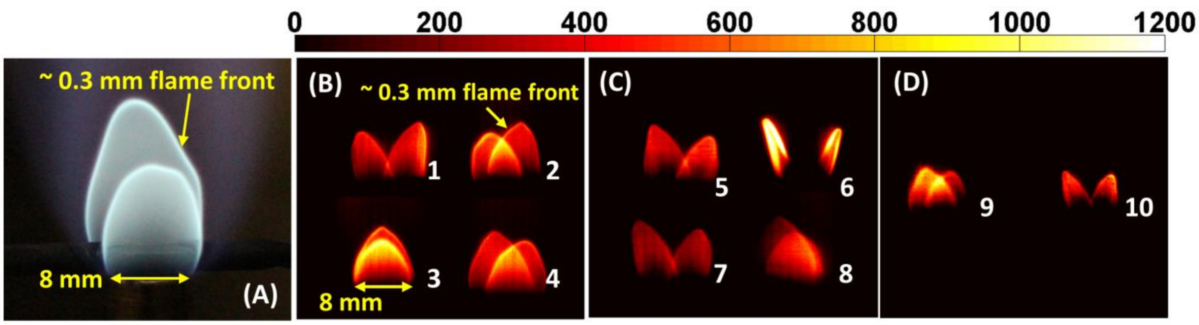
2.5. Use of Fiber Bundles in Volumetric Tomography

This objective was successfully completed as detailed in [15] and [16].

We have developed customized fiber endoscopes and demonstrate them in a variety of 3D measurement campaigns, ranging from laboratory flames to a Mach 2 combustor. Figures 7, 8, and 9 show an example set of results taken out of [15] to illustrate the technique. Figure 7 illustrates the use of fiber endoscopes to combine multiple projections onto the same camera, Figure 8 shows 10 simultaneous projections captured using the fiber endoscopes and a total of three cameras, and Figure 9 shows the 3D reconstruction of the flame structure based on the projections.



Figures 12. Experiment setup and problem formulation. Inset on upper right corner shows a photograph of a fiber endoscope with four inputs and one output.



Figures 13: Photograph of a V-flame. (B)-(D): Ten simultaneous projections captured on three cameras using three fiber endoscopes.

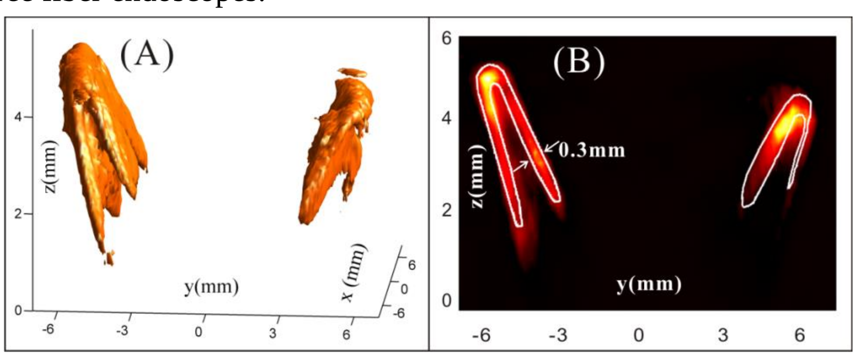


Figure 14. (A): 3D reconstruction of the V-flame. (B): a cross-sectional view at along x=0.

2.6. Data Analysis and Post Processing

This objective was completed and summarized in [17] and [18].

We have developed algorithms to extract key physics from the 4D datasets (three spatial dimensions and time) enabled by the volumetric diagnostics listed above. These algorithms included algorithms to extract flame topography, surface area, 3D curvature, and multi-dimensional POD (proper orthogonal decomposition). Two examples of the data analysis and processing algorithms are shown in Figure 15. The left panel of Figure 10 shows the 3D flame curvature extracted from VCHEM measurement on a highly turbulent Bunsen flame (the data was taken from [5]), and the right panel shows the second eigenmode of the flames stabilized in a Mach 2 combustor obtained via multi-angular proper orthogonal decomposition (POD) (the data was taken from [17]).

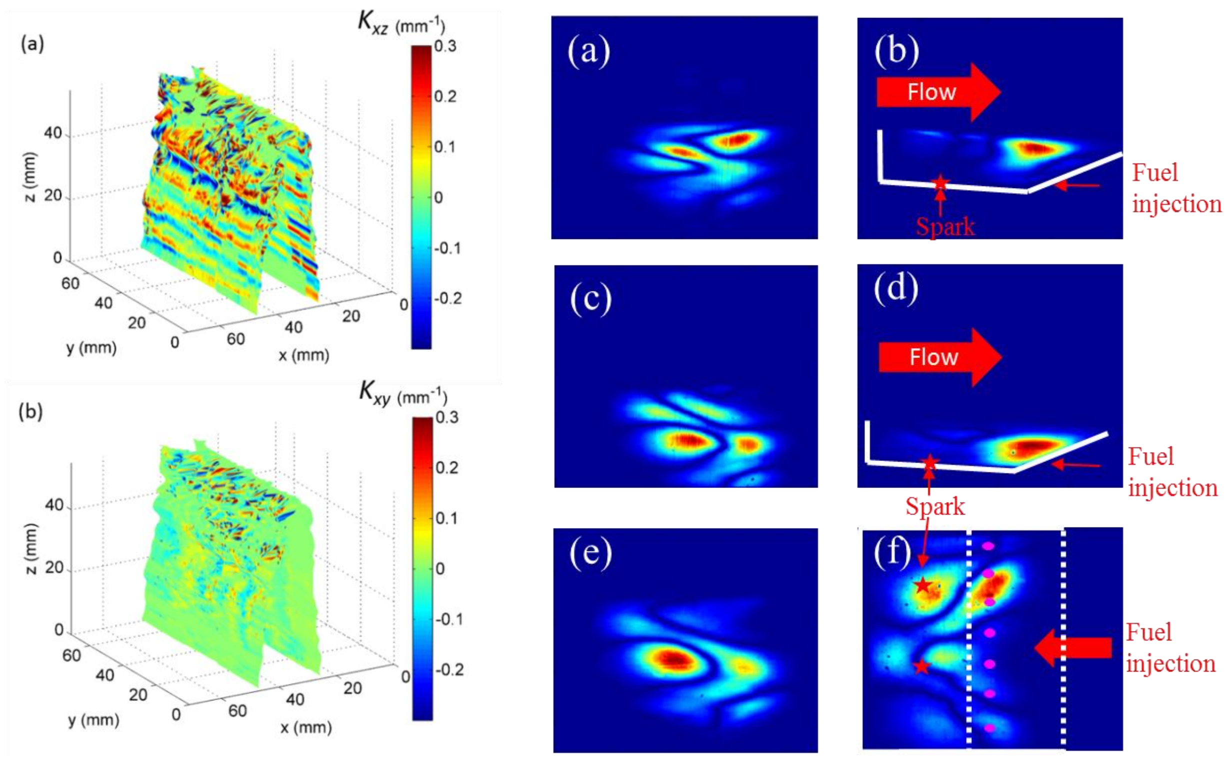


Figure 15. Left: 3D curvature on a flame front extracted from 3D VCHEM technique. Right: the second eigenmode from 6 different orientations of fuel-rich flames measured in a Mach 2 combustor .

3. Air Force Laboratory and Other Collaborations

The PI also proposed several collaborative activities in this project to maximize its impact and promote AFOSR's vision and mission. In this project, the PI has collaborated with Drs. Campbell Carter and Tim Ombrello to perform volumetric measurements in the combustion facilities at WPAFB. The PI has visited WPAFB regularly (WPAFB is approximately 6 hours of driving from Virginia Tech), and he has been awarded the Summer Faculty Fellowship three times (2014, 2015, and 2016) and spent extended time on-site at WPAFB during these summers.

These collaborations successfully pooled together the resources and expertise between the PI's group and the WPAFB groups to address issues of importance for the Air Force, for example, exploring the 3D nature of the ignition and transition processes under high Mach numbers and enabling 3D data in highly turbulent flames. These collaborations also provided a great opportunity for the PI and his students to participate in critical research at cutting-edge laboratories, for the enhancement of both science and education.

4. Publications from this grant

Referred Journal Publications

[15]. Xu, W., Carter, C.D., Hammack, S.D., Ma, L., Analysis of 3D combustion measurements using CH-based tomographic VLIF (volumetric laser induced fluorescence), Combustion and Flame, submitted, Dec 2016.

[14]. Ma, L., Lei, Q., Capil, T., Hammack, S.D., Cater, C.D., Direct comparison of 2D and 3D LIF measurements on highly turbulent flames, Optics Letters, Accepted, Dec 2016.

[13]. Lei, Q., Xu, W., Wu, Y. and Ma, L., "Development and validation of a reconstruction algorithm for three-dimensional nonlinear tomography problems". Optics Express, 24(14), p15912-15926, July 2016.

[12]. Ma, L., Wu, Y., Xu, W., Hammack, S., Lee, T., Carter, C.D., Comparison of 2D and 3D flame topography measured by PLIF and tomographic chemiluminescence, Applied Optics,55(20), p5310-5315, 2016.

[11]. Ma, L., Lei, Q., Ikeda, J., Xu, W., Carter, C.D. Single Shot 3D Flame Diagnostic Based on Volumetric Laser Induced Fluorescence (VLIF), Proceedings of the Combustions Institute, Published July 2016

[10] Ma, L., Non-intrusive and Multidimensional Optical Diagnostics and Their Applications in the Study of Thermal-Fluid Systems, Heat Transfer Engineering, 37(3-4), 359-368, (2016)

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Grant/Contract Number
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FA9550-14-1-0386

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Lin Ma

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The AFOSR Program Officer currently assigned to the award

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Abstract

This two-year project is aimed at establishing advanced diagnostics techniques for obtaining volumetric measurement of key combustion properties. The proposed techniques are designed to generate instantaneous volumetric (i.e., three-dimensional, 3D) data without scanning or raster, and thusly to enable measurement rate in the multi-kilohertz range, directly addressing a key experimental need identified in the BAA. Six specific topics have been investigated during this project: 1) the establishment of a unified framework for volumetric tomography, 2) the investigation and validation of Volumetric Chemiluminescence imaging (VCHEM), 3) the investigation and validation of Volumetric Laser Induced Fluorescence (VLIF), 4) the investigation and validation of Volumetric Particle Image Velocimetry (VPIV), 5) the use of fiber bundles in volumetric tomography, and 6) algorithms for data Analysis and post processing.

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Technical Summary

Funding Summary by Cost Category (by FY, $K)

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